A New Approach to Evaluate the Impact of Climate on Human Mortality

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The objective of this study is to introduce a new procedure to determine the impact of climate on human mortality with the use of a synoptic climatological approach. The holistic nature of synoptic categories allows for the simultaneous evaluation of numerous weather elements as they realistically appear within air masses. In addition, this approach allows for a better distinction between pollution-induced mortality and weather-induced mortality. A synoptic categorization was performed for St. Louis, Missouri, and each category was evaluated in terms of its mean daily mortality. Of 10 summer categories found in St. Louis, one possessed the highest mean mortality by far, and 8 of the top 10 mortality days in St. Louis occurred when this category was present. Further analysis determined that long, consecutive day periods of this hot, oppressive category are associated with a continuing rise in mortality. It was determined that the procedure described here has the potential to be used in a weather/mortality watch-warning system. Finally, it appears that day-to-day mortality fluctuations are much more sensitive to weather than to pollution concentrations, as the oppressive category associated with the greatest mortality possessed levels of six major pollutants that were not noteworthy.

Introduction

The impact of variable climate on human health and well-being has been the subject of numerous studies, with the majority of the work being performed by medical specialists and a small minority by climatologists. With the threat of an anthropogenic-induced global warming, the interest in climate/human health studies has increased, and at least three comprehensive reports summarizing most of this research have appeared in recent years (1–3).

The majority of the climate/human health evaluations have concentrated on mortality, and virtually all of the studies correlate a number of climate variables with daily or weekly mortality statistics. For example, medical researchers have noted that mortality attributed to weather seems to vary considerably with age, sex, and race, although there is disagreement in defining the most susceptible population group (4–6). Some researchers have found that many causes other than heat stroke increase during extreme weather (7,8). Evaluations have been performed for winter weather impacts as well, and mortality increases have been noted during extreme cold waves (6–11). More recent studies have concentrated on interregional impacts of weather on human health, and the potential adverse effects of global climate change (12,13). In addition, the sophistication of climatic modeling within these has increased, and "threshold temperatures," which represent the temperature beyond which mortality significantly increases, have been identified for numerous cities (14).

All of these studies suffer from at least two shortcomings. First, the use of individual weather elements to evaluate the impact of climate on human health may provide misleading results. Climate affects human health as a holistic unit composed si-

multaneously of numerous climatic elements that react in concert. Thus, the isolation of individual elements can represent an unrealistic situation that does not duplicate climatic reality. Second, the impact of pollution concentration is often ignored in a climate/mortality evaluation. It is possible that the mechanisms responsible for increasing mortality are truly pollution-oriented, but these are imbedded (and ignored) within the climate evaluation. It is not feasible to evaluate individual pollutants (e.g., SO_2 or NO_2 concentrations) along with individual climate elements (e.g., temperature or dew point) as independent variables within a health study because the climate and pollution variables are somewhat collinear.

The objective of this study is to introduce a new procedure to determine the impact of climate on human mortality that does not suffer from the problems outlined above. This involves the use of a synoptic climatological approach, which combines weather elements into groups or categories that are representative of true meteorological situations at a moment in time (15). Synoptic climatological approaches characterize similarities in general circulation patterns and active meteorological elements within a holistic framework, facilitating analyses of climate's impact on a variety of environmental variables such as human mortality. Thus, the impact of the totality of weather on the environmental variable can be determined. Additionally, synoptic categories possess differential abilities to retain high concentrations of pollutants. Thus, certain synoptic categories are usually associated with low pollutant concentrations, while others are almost always highly polluted. Kalkstein and Corrigan (16) determined that the 9 most polluted days in Wilmington, Delaware, during the winters of 1974–1978 were associated with two synoptic categories that occurred only 15% of the time during the period. It is clear that this approach can distinguish between offensive weather situations and offensive pollution situations.

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Methodology

The National Center for Health Statistics (NCHS) provided us with a very detailed mortality database that contains records of every person who died in the United States from 1964 to the present [refer to NCHS (17) for a detailed description of these records]. We selected St. Louis, Missouri, for our test location, as previous research suggests that the area is particularly sensitive to heat-related deaths (14). The data contain cause of death, place of death, age, date of death, and race, and these were extracted for the St. Louis Standard Metropolitan Statistical Area for 11 years: 1964–66, 1972–78, and 1980 (although the data are complete for the entire record, during intervening years the date of death was omitted). The number of deaths for each day was tabulated and divided into categories based on age (all ages and elderly, classified as greater than 65 years old) and race (white and nonwhite).

All mortality data were adjusted to account for changes in the age, racial distribution, and total population of the St. Louis area during the period of record. A direct standardization procedure was used, and a standard population was constructed for each of the evaluated mortality categories [refer to Mausner and Bahn (18) and Lilienfield and Lilienfield (19) for a discussion of this standardization procedure].

An automated air-mass-based synoptic climatological index was developed for St. Louis to categorize each day into its particular synoptic category. The synoptic procedure is designed to classify days that are considered to be meteorologically homogeneous. This is accomplished by defining each day in terms of seven readily available meteorological elements, which include air temperature, dew point temperature, visibility, total cloud cover, sea-level air pressure, wind speed, and wind direction. There elements are measured four times daily (0100, 0700, 1300, 1900 hr local standard time), and the developed 28 variables represent the basis for categorization.

The developed temporal synoptic index (TSI) uses principal components analysis (PCA), a factor analysis technique that rewrites the original data matrix into a new set of components that are linearly independent and ordered by the amount of variance they explain [for a detailed explanation of this procedure, refer to Kalkstein et al. (20)]. Component loadings are calculated, which express the correlation between the original 28 variables and the newly formed components. Each day is then expressed by its particular set of "component scores," which are weighted summed values whose magnitudes are dependent on the weather observation for each day and the principal component loading. Thus, days with similar meteorological conditions will tend to exhibit proximate component scores.

A clustering procedure was then used to group those days with similar component scores into meteorologically homogeneous groups. There are numerous clustering methodologies available, but the one deemed most efficient in the development of a synoptic climatological index is the average linkage method (20). Once the groups have been determined, average values are calculated for the 28 meteorological variables for all days within each particular group. Weather map classification is also possible by reviewing maps for those days within a group and describing general similarities.

The mean daily mortality for each synoptic category, along with the standard deviation, was then determined to ascertain whether particular categories were distinctively high or low. Potential lag times were accounted for by evaluating the daily synoptic category on the day of the deaths, as well as 1, 2, and 3 days before the day of the deaths. Daily mortality was then sorted from highest to lowest during the period of record to determine whether certain synoptic categories were prevalent near the top or bottom.

Mean daily pollution concentrations were also examined for each synoptic category in an attempt to determine if the synoptic situations associated with the highest mortailty are also the most polluted. The EPA made available mean daily pollution concentrations for six raw pollutants at several automatic recording monitoring stations in the St. Louis area. The monitor with the most complete record was selected for this study, and mean daily values of the following pollutants were extracted: total suspended particulates (TSP), NO_x, NO_2, total oxidants, O_3, and SO_2. It was also noted whether the highest mortality days within each synoptic category were the most polluted.

Results

Synoptic Categorization

Ten major summer synoptic categories were uncovered for St. Louis and were identified based on their mean meteorological characteristics (Table 1). Two hot, oppressive synoptic situations, categories 6 and 9, were identified, with the latter being more extreme. Several anticyclonic categories were identified, which generally possess the most stable atmospheric situations. Two categories (4 and 8) were frequently associated with convective precipitation patterns and represented unstable atmospheric conditions.

Mean pollution concentrations varied considerably between categories (Table 2). The three anticyclonic synoptic patterns (categories 1, 2, and 3) generally possessed the highest concentrations for most of the pollutants. Category 2 exhibited the highest mean TSP, ozone, and NO_x concentrations, while category 1 was highest for NO_2 and oxidants. The only exception was for SO_2, where the highest concentrations were found within maritime tropical category 5. The two hottest synoptic situations, categories 6 and 9, were generally not distinctive, except for a moderately high TSP reading for category 6. The most oppressive synoptic situation, category 9, generally possessed mean pollutant readings near or below the overall norm. A cursory evaluation of the very hottest category 9 days indicated that they were no more polluted than any of the other days within the category.

Mortality Associations

An evaluation of mortality for the 10 synoptic categories uncovered some startling results (Table 3). After examining the potential lag-time relationships, it was determined that a 1-day lag existed between the causal synoptic mechanism and the mortality response (the between-category differential in mean daily mortality was greatest for a 1-day lag situation), with mean mortality values up to 52% higher than the other categories. The distinction between category 9 and the other synoptic situations

Table 1. Mean meterorological characteristics for the 10 synoptic categories.

Category	Description	Category frequency[a]	Time, hr	T_a, °F[b]	T_d, °F[c]	Pressure, mb	Visibility, km	Cloud cover, tenths	Wind[d]
1	Anticyclonic, continental	18.7	0100	63	56	1019	12	2	NE, light
			0700	73	56	1021	11	3	
			1300	82	55	1019	13	4	
			1900	71	57	1019	12	2	
2	Anticyclonic, transitional	10.7	0100	68	62	1018	8	2	SE, moderate
			0700	79	64	1020	7	4	
			1300	87	63	1018	9	5	
			1900	77	64	1018	9	3	
3	Anticyclonic maritime	12.1	0100	72	68	1016	6	4	SSE, moderate
			0700	79	70	1018	5	7	
			1300	86	70	1016	7	8	
			1900	78	70	1016	7	6	
4	Weak wave, overcast	8.7	0100	69	66	1014	8	8	SW, light
			0700	73	66	1016	6	9	
			1300	78	66	1015	8	9	
			1900	71	66	1015	8	7	
5	Maritime tropical, cloudy	17.4	0100	74	68	1013	9	5	SW, strong
			0700	80	70	1014	10	7	
			1300	88	70	1012	11	7	
			1900	79	70	1013	11	6	
6	Maritime tropical, sunny	6.5	0100	75	68	1017	10	1	SSW, strong
			0700	84	70	1018	9	2	
			1300	93	68	1016	11	4	
			1900	83	70	1016	10	3	
7	Continental to maritime transition	10.0	0100	70	64	1013	12	4	W, moderate
			0700	78	65	1015	12	5	
			1300	86	64	1013	14	6	
			1900	76	64	1014	13	4	
8	Maritime unsettled	2.5	0100	72	68	1009	9	7	WSW, strong
			0700	76	69	1010	9	9	
			1300	83	69	1009	11	9	
			1900	74	68	1010	10	7	
9	Oppressive tropical (some continental influence)	7.0	0100	78	69	1014	12	2	SE, strong
			0700	86	70	1015	12	2	
			1300	96	68	1012	14	4	
			1900	86	70	1013	13	2	
10	Continental polar, recent frontal passage	6.4	0100	64	59	1013	12	5	NW, moderate
			0700	70	57	1015	13	6	
			1300	77	55	1014	14	6	
			1900	67	56	1015	14	3	

[a]Percent of total days within each category.
[b]Air temperature.
[c]Dew point temperature.
[d]Wind direction and speed.

was especially strong for elderly and nonwhite mortality. Interestingly, the second hottest synoptic situation, category 6, possessed mortality means that were almost identical to the other nondistinctive categories. This seems to imply that weather-induced mortality rises dramatically only after a particular oppressive threshold is exceeded. It appears that only category 9 possesses conditions that exceed this threshold for St. Louis.

It is noteworthy that almost all the highest mortality days in St. Louis occurred when category 9 was present (Table 4). For total mortality, 8 of the 10 highest days occurred under the domination of category 9, even though this oppressive category occurred

only 7% of the time during the period of study. This finding suggests that a vast majority of deaths that can be attributed to weather occur only when category 9 is present. For the 20 highest mortality days, category 9 was present 11 times. Although this is a bit less impressive, this still represents 8 times the expected occurrence of category 9 over a typical 20-day period. Category 6 only occurred once within the top 20 mortality days, further suggesting that the second hottest synoptic category is not oppressive enough to induce any extra deaths. Categories 3 (anticyclonic, marine influence) and 5 (maritime tropical, cloudy) are present among the top 20 days, but their frequencies are

Table 2. Mean daily pollutant concentrations for each synoptic category for St. Louis.

Category number	Pollutant, ppm[a]					
	TSP[b]	NOx	NO₂	OXI	O₃	SO₂
1	87.0	0.004	0.023	0.026	0.023	0.051
2	103.2	0.009	0.019	0.020	0.025	0.050
3	100.8	0.005	0.020	0.020	0.018	0.032
4	90.1	0.002	0.022	0.018	0.020	0.022
5	84.6	0.007	0.016	0.018	0.020	0.080
6	100.8	0.004	0.017	0.021	0.021	0.028
7	69.9	0.006	0.020	0.011	0.022	0.029
8	75.9	0.003	0.018	0.023	0.015	0.060
9	87.8	0.001	0.020	0.022	0.016	0.041
10	74.1	0.004	0.014	0.021	0.023	0.017

[a]TSP, total suspended particulates; NOx, nitrous oxides, not including nitrogen dioxide; NO₂, nitrogen dioxide; OXI, total oxidants; O₃, ozone; SO₂, sulfur dioxide.

[b]Units are micrograms/cubic meter for TSP.

Table 3. Mean daily mortality for each synoptic category for St. Louis.

Category number	Mean mortality for[a]			
	Whites	Nonwhites	Elderly	Total[b]
1	69	25	60	94
2	71	29	63	100
3	71	27	63	98
4	68	25	59	93
5	72	28	64	100
6	73	30	64	103
7	70	27	60	97
8	70	25	60	95
9	88	41	84	129
10	68	25	59	93
Overall mean excluding category 9	70	27	62	97
Percent category 9 exceeds overall mean	26	52	36	33

[a]Values represent a 1-day lag between synoptic category occurrence and mortality response.

[b]Total equals the sum of the white and nonwhite values.

Table 4. Synoptic category of the 10 and 20 highest mortality days in St. Louis.

Total mortality		Elderly mortality	
Category number	Frequency	Category number	Frequency
10 highest days			
9	8	9	7
3	1	3	1
5	1	5	1
		6	1
20 highest days			
9	11	9	11
5	4	3	3
3	3	1	2
6	1	4	1
7	1	5	1
		6	1
		7	1

not much different from their expected occurrence over any typical 20-day period.

Standard deviations in mortality within the 10 synoptic types indicate further that category 9 is distinctive (Table 5). The standard deviations for all the synoptic situations are somewhat similar with the very apparent exception of category 9, which possesses values about three times higher than the other categories. This indicates that, although most of the highest mortality days are associated with category 9, numerous days within this synoptic type possess much lower mortality totals. An evaluation of all days within category 9 confirms this assumption, and numerous category 9 days exhibit mortality totals at or sometimes below the means of the other synoptic types.

In an attempt to understand why daily mortality shows such considerable variation within category 9, a detailed within-category evaluation was performed for total and elderly mortality. The objective was to determine which meteorological and pollution-oriented aspects of synoptic category 9 are responsible for the highest mortality. To evaluate the impact of pollution, all category 9 days were sorted from highest to lowest mortality, and concentrations of the various pollutants were noted for each day (a considerable number of pollution values were mis-

sing, necessitating a qualitative, rather than quantitative, evaluation). It was apparent that concentrations were not related to within-category mortality, as the highest pollutant concentrations did not occur on the highest mortality days.

To evaluate the impact of within-category variations in meteorology, a stepwise multiple regression analysis was performed on all days for category 9 with daily mortality as the dependent variable (this analysis was performed for total and elderly mortality). The independent variables included the following weather elements: maximum temperature, minimum temperature, mean daily cloud cover, maximum dew point temperature, minimum dew point temperature, morning visibility, afternoon visibility, morning windspeed, afternoon windspeed, and a heat duration variable that measures the daily duration, rather than the intensity, of the heat. The duration variable determines whether a day with the temperature hovering near 95 °F for many hours appears to have a greater influence on mortality than a day where the temperature exceeds 100 °F for a short time but falls rapidly to more tolerable levels [refer to Kalkstein and Davis (14) for details on the computation]. A final nonmeteorological independent variable was included, "day in sequence," which noted how a particular category 9 day was positioned within a consecutive day sequence. For example, if the day in question was the third of a category 9 consecutive day sequence, it was assigned a value of 3. All single-day category 9 days that were not part of a consecutive sequence were assigned a value of 1.

The results explained much of the variance in mortality within category 9 (Table 6). The day in sequence variable explained the largest proportion of the variance in both the total and elderly mortality models, and the direct relationship indicated that a category 9 day near the end of a consecutive day sequence is most

Table 5. Standard deviations for the synoptic categories.

Category number	Whites	Nonwhites	Elderly	Total
1	10.85	8.65	11.52	13.58
2	10.47	9.71	12.35	14.42
3	12.18	10.55	13.84	16.71
4	10.79	10.32	12.16	15.10
5	13.97	12.67	17.00	20.18
6	10.76	10.47	11.81	14.85
7	11.24	8.53	12.44	14.94
8	9.22	9.86	8.15	12.49
9	34.27	24.67	44.20	52.49
10	10.59	8.13	11.04	13.34

Table 6. Results of category 9 regression analysis between mortality and various climatic elements.

Variable	Parameter estimate	SE	Probability >t	VIF[a]	Model probability >F	R²[b]
Total mortality						
Intercept	-220.59					
Day in sequence[c]	22.39	5.19	0.0001	1.41		
PM Windspeed	-5.47	1.45	0.0004	1.01		
Minimum temperature	4.41	1.27	0.0010	1.44		
PM Visibility	2.73	1.49	0.0737	1.05		
Total model					0.0001	0.5662
Elderly mortality						
Intercept	-116.79					
Day in sequence	20.78	4.58	0.001	1.38		
PM Windspeed	-4.61	1.29	0.0007	1.01		
Minimum temperature	2.86	1.11	0.0127	1.38		
Total model					0.0001	0.5104

[a]All variables in the models have been tested for collinearity by using variance inflation factors (VIFs). A VIF of 2.0 or less indicates that the independent variables are not collinear (26).
[b]This value represents an adjusted R², which has been adjusted for degrees of freedom in the model.
[c]This is the day-in-sequence variable. Refer to text for explanation.

important. Thus, a long consecutive day sequence of category 9 days imposes the greatest amount of stress as expressed by increasing mortality through the sequence. Afternoon wind speed was the second-ranking independent variable in both models, and low wind speeds seem to exacerbate stressful conditions. This finding runs counter to some studies that indicate that higher wind speeds at very warm temperatures increase stress on the body (21,22). Not surprisingly, minimum temperature was a statistically significant variable and was directly related to mortality within category 9. However, maximum temperature was not significant in either the total or elderly models. Visibility was quite important in the total mortality model, and fell just short of statistical significance at the 0.05 level. Interestingly, visibility was directly related, indicating that visibility-reducing high pollution concentrations are not important contributors to increased mortality. Rather, this relationship might imply that the heat load imposed by a transparent atmosphere that increases insolation might be important by further increasing stress.

Discussion and Conclusion

One of the major findings from this synoptic evaluation is evidence suggesting that fluctuations in daily mortality appear to be much more sensitive to stressful weather than to high levels of pollution. Those anticyclonic synoptic categories with the highest mean pollution concentrations were not associated with unusually high numbers of deaths. Conversely, category 9, which was associated with the highest daily mortality totals, did not possess high mean pollution concentrations for the six pollutants examined. Further, those days within category 9 that were among the top 20 mortality days through the period of study exhibited pollution concentrations somewhat near (and sometimes below) the mean.

These findings run counter to research involving mortality and air pollution in London (23) and morbidity and air pollution in Los Angeles (24). The London study detected a significant relationship between high mortality and British smoke (particulates), while the Los Angeles study noted that chest discomfort, eye irritation, and headache probabilities were associated with high NO_2 and SO_2 concentrations.

It is quite possible that pollution levels in London are often higher than those in St. Louis, as stringent U.S. clean air laws might keep pollutant levels below health-damaging thresholds. To determine if this was the case, a cursory evaluation similar to the St. Louis analysis was performed for 9 additional U.S. cities (Table 7), and synoptic indices were developed for each of them. Preliminary results indicated that 7 of the 10 cities evaluated (including St. Louis) possessed strong or moderate weather/mortality signals as demonstrated by a particular synoptic category which possessed unusually high mean daily mortality. None of the cities showed any pollutant/mortality signal, as demonstrated by a particular synoptic category with elevated pollutant concentrations which possessed unusually high mean daily mortality. Although these results are preliminary, they seem to support the findings of the St. Louis study.

Table 7. A cursory comparison of the relative impacts of pollution concentration and weather on mortality for 10 selected U.S. cities.[a]

Strong weather mortality signal	Boston
	Memphis
	New York City
	Philadephia
	St. Louis
Moderate weather/mortality signal	Chicago
	San Francisco
No weather/mortality signal	Atlanta
	Dallas
	Seattle
Strong pollution/mortality signal	None
Moderate pollution/mortality signal	None
No pollution/mortality signal	Atlanta
	Boston
	Chicago
	Dallas
	Memphis
	New York City
	Philadelphia
	St. Louis
	San Francisco
	Seattle

[a] To have a moderate or high weather/mortality signal, a city must possess a synoptic category that has an unusually high mean daily mortality. To have a moderate or high pollution/mortality signal, a city must possess a synoptic category with an elevated pollution level that has an unusually high mean daily mortality. In this preliminary analysis, this was determined subjectively.

Another interesting result is the absence of maximum temperature as a significant variable within the category 9 regression models, a surprising finding considering the importance of minimum temperature within both models. This supports a contention made in a previous nonsynoptic climate/mortality study that suggests that oppressive nighttime conditions offering little relief after a very hot day might be more stressful than the maximum temperature itself (*14*).

The results of this evaluation strongly suggest that the synoptic climatological approach is more robust than traditional climatological procedures in the evaluation of weather/mortality relationships. It was noteworthy that only 1 of 10 synoptic categories which are present in St. Louis during summer is oppressive enough to raise daily mortality beyond baseline levels. This supports the notion that mortality does not increase linearly as weather becomes increasingly stressful. Rather, threshold conditions exist beyond which mortality significantly increases in abrupt fashion.

It is possible that the procedure described here has the potential to be used in a weather/mortality watch-warning system, designed to warn of impending meteorological conditions that could raise mortality significantly among high-risk groups such as the elderly. For example, if a category 9 synoptic situation is approaching, a within-category evaluation can be performed based on the regression analyses presented in Table 6. According to Box and Wetz (*25*), a regression model may be considered to be a worthwhile predictor if the actual *F*-ratio is larger than some multiple of the critical *F*. The magnitude of this multiple is dependent on the degrees of freedom. Using the criteria set forth by Box and Wetz (*25*), the two models presented in Table 6 are acceptable predictors for summer mortality. At this point in the study, no model validation has yet been performed, and the results of this paper should be considered for analytical content rather than predictive capabilites. However, the next stage in this research will involve a detailed evaluation of the nine additional cities to add further credence to this methodology. In addition, model validation on a data set not used in model development is neccessary to determine if, in fact, this procedure has predictive value in a weather/mortality watch-warning system.

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